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CHAPTER 19

CONCENTRIC NEUTRAL CORROSION

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1. INTRODUCTION

In nature, metals are usually found in combinations such as oxides or sulfides, not as a pure metal. Nature wants to change those pure metals back to their original state after we have refined them to an almost pure metal. That process is known as corrosion [19-1, 19-2, 19-3].

Corrosion may be defined as the destruction of metals by chemical or electrochemical reaction with the environment. The fundamental reaction involves a transfer of electrons where in a moist or wet environment some positive ions lose electrical charges. These positive charges are acquired by the metallic member and a portion of the metal surface goes into solution, hence is corroded. The entire process may be divided into an anodic reaction (oxidation) and a cathodic reaction (reduction). The anodic reaction represents acquisition of charges by the corroding metal and the cathodic reaction represents the loss of charges by hydrogen ions that are discharged. The flow of electricity between the anodic and cathodic areas may be generated by local cells set up either on a single metallic surface, or between dissimilar metals.

1.1 Electromotive Series

The tendency for metals to corrode by hydrogen ion displacement is indicated by their position in the electromotive series shown in Table 19-1. To achieve these precise voltages, the metals must be in contact with a solution in which the activity of the ion indicated is one mol per 1,000 grams of water and at 77°F (25°C). Different values of voltage will be obtained in other solutions.

Metals above hydrogen displace hydrogen more readily than do those below hydrogen in this series. A decrease in hydrogen ion concentration (acidity), tends to move hydrogen up relative to other metals. An increase in the metal ion concentration tends to move the metals down relative to hydrogen. Whether or not hydrogen evolution will occur in any case is determined by several other factors besides the concentration of hydrogen and metallic ions.

Table 19-1
Electromotive Series

(Anodic End)

Metal	Ion	Volts
Magnesium	$\text{Mg} + 2\text{e}^*$	-2.34
Aluminum	$\text{Al} + 3\text{e}$	-1.67
Zinc	$\text{Zn} + 2\text{e}$	-0.76
Chromium	$\text{Cr} + 3\text{e}$	-0.71
Iron	$\text{Fe} + 2\text{e}$	-0.44
Cadmium	$\text{Cd} + 2\text{e}$	-0.40
Nickel	$\text{Ni} + 2\text{e}$	-0.25
Tin	$\text{Sn} + 2\text{e}$	-0.14
Lead	$\text{Pb} + 2\text{e}$	-0.13
Hydrogen	$\text{H} + \text{e}$	Arbitrary 0.00
Copper	$\text{Cu} + 2\text{e}$	+0.34
Silver	$\text{Ag} + \text{e}$	+0.80
Palladium	$\text{Pd} + 2\text{e}$	+0.83
Mercury	$\text{Hg} + 2\text{e}$	+0.85
Carbon	$\text{C} + 2\text{e}$	+0.90
Carbon	$\text{C} + 4\text{e}$	+0.90
Platinum	$\text{Pt} + 2\text{e}$	+1.2
Gold	$\text{Au} + 3\text{e}$	+1.42
Gold	$\text{Au} + \text{e}$	+1.68

(Cathodic End)

* Note: "e" stands for electrons (negative charges)

1.2 Electrochemical Equivalents

The electrochemical equivalent of a metal is the theoretical amount of metal that will enter into solution (dissolve) per unit of direct current transfer from the metal to an electrolyte. Table 19-2 shows that theoretical amount of metal removed in pounds per year with one ampere of direct current flowing continuously from the material.

Table 19-2
Electrochemical Equivalents

Metal	Pounds Removed per Amp per Year
Carbon (C++++)	2.16
Carbon (C++)	4.23
Aluminum	6.47
Magnesium	8.76
Chromium	12.5
Iron	20.1
Nickel	21.1
Cobalt	21.2
Copper (Cu++)	22.8
Zinc	23.5
Cadmium	40.5
Tin	42.7
Copper (Cu+)	45.7
Lead	74.2

1.3 Hydrogen Ion Concentration

A normal solution is one that contains an "equivalent weight" (in grams) of the material dissolved in sufficient water to make one liter of the solution. The equivalent weight of hydrogen is 1 and therefore one gram of hydrogen ions in a liter of water is a normal acid solution. The hydroxyl ion has an equivalent weight of 17 (1 for the hydrogen and 16 for oxygen). Therefore, 17 grams in a liter is equal to the normal alkaline solution.

Since acids produce hydrogen ions when dissolved in water, the concentration of the hydrogen ions is a measure of the acidity of the solution. The hydrogen ion concentration is expressed in terms of pH. Stated mathematically, the pH value is the logarithm of the reciprocal of the hydrogen ion concentration in terms of the normal solution. A change of one in pH value is equivalent to a change of ten times in concentration.

In any aqueous solution, the hydrogen ion concentration multiplied by the hydroxyl ion concentration is always a constant. When the concentrations are expressed in terms of normal solution, the constant is equal to 10^{-14} . It follows that a solution having a pH equal to 7 is neutral, less than 7 has an acidic reaction, and more than 7 has an alkaline reaction

Table 19-3
Significance of Hydrogen Ion Concentration

pH	Hydrogen Ion Concentration	Hydroxyl Ion Concentration	Reaction
0	1.0×10^{-0}	1.0×10^{-14}	Acidic
1	1.0×10^{-1}	1.0×10^{-13}	Acidic
2	1.0×10^{-2}	1.0×10^{-12}	Acidic
3	1.0×10^{-3}	1.0×10^{-11}	Acidic
4	1.0×10^{-4}	1.0×10^{-10}	Acidic
5	1.0×10^{-5}	1.0×10^{-9}	Acidic
6	1.0×10^{-6}	1.0×10^{-8}	Acidic
7	1.0×10^{-7}	1.0×10^{-7}	Neutral
8	1.0×10^{-8}	1.0×10^{-6}	Alkaline
9	1.0×10^{-9}	1.0×10^{-5}	Alkaline
10	1.0×10^{-10}	1.0×10^{-4}	Alkaline
11	1.0×10^{-11}	1.0×10^{-3}	Alkaline
12	1.0×10^{-12}	1.0×10^{-2}	Alkaline
13	1.0×10^{-13}	1.0×10^{-1}	Alkaline
14	1.0×10^{-14}	1.0×10^{-0}	Alkaline

2. TYPES OF CORROSION

There are numerous types of corrosion, but the ones that are discussed here are the ones that are most likely to be encountered with underground power cable facilities.

In this initial explanation, lead will be used as the referenced metal. Copper neutral wire corrosion will be discussed as a separate topic later.

2.1 Anodic Corrosion (Stray dc Currents)

Stray dc currents come from sources such as welding operations, flows between two other structures, and -- in the days gone by -- street railway systems.

Anodic corrosion is due to the transfer of direct current from the corroding facility to the surrounding medium--usually earth. At the point of corrosion, the voltage is always positive on the corroding facility. In the example of lead sheath corrosion, the lead provides a low resistance path for the dc current to get back to its source. At some area remote from the point where the current enters the lead, but near the inception point of that stray current, the current leaves the lead sheath and is again picked up in the normal dc return path. The point of

entry of the stray current usually does not result in lead corrosion, but the point of exit is frequently a corrosion site.

Clean sided corroded pits are usually the result of anodic corrosion. The products of anodic corrosion such as oxides, chlorides, or sulfates of lead are carried away by the current flow. If any corrosion products are found, they are usually lead chloride or lead sulfate that was created by the positive sheath potential that attracts the chloride and sulfate ions in the earth to the lead.

In severe anodic cases, lead peroxide may be formed. Chlorides, sulfates, and carbonates of lead are white, while lead peroxide is chocolate brown.

2.2 Cathodic Corrosion

Cathodic corrosion is encountered less frequently than anodic corrosion--especially with the elimination of most street railway systems.

This form of corrosion is usually the result of the presence of an alkali or alkali salt in the earth. If the potential of the metal exceeds -0.3 volts, cathodic corrosion may be expected in those areas. In cathodic corrosion, the metal is not removed directly by the electric current, but it may be dissolved by the secondary action of the alkali that is produced by the current. Hydrogen ions are attracted to the metal, lose their charge, and are liberated as hydrogen gas. This results in a decrease in the hydrogen ion concentration and the solution becomes alkaline.

The final corrosion product formed by lead in cathodic conditions is usually lead monoxide and lead / sodium carbonate. The lead monoxide formed in this manner has a bright orange / red color and is an indication of cathodic corrosion of lead.

2.3 Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals in an electrolyte have a metallic tie between them. One metal becomes the anode and the other the cathode. The anode corrodes and protects the cathode as current flows in the electrolyte between them. The lead sheath of a cable may become either the anode or the cathode of a galvanic cell. This can happen because the lead sheath is grounded to a metallic structure made of a dissimilar metal and generally has considerable length. Copper ground rods are frequently a source of the other metal in the galvanic cell.

The corrosive force of a galvanic cell is dependent on the metals making up the electrodes and the resistance of the electrolyte in which they exist. This type of

corrosion can often be anticipated and avoided by keeping a close watch on construction practices and eliminating installations having different metals connected together in the earth or other electrolyte.

2.4 Chemical Corrosion

Chemical corrosion is damage that can be attributed entirely to chemical attack without the additional effect of electron transfer. The type of chemicals that can disintegrate lead are usually strong concentrations of alkali or acid. Examples include alkaline solutions from incompletely cured concrete, acetic acid from volatilized wood or jute, waste products from industrial plants, or water with a large amount of dissolved oxygen.

2.5 AC Corrosion

Until about 1970, ac corrosion was felt to be an insignificant, but possible, cause of cable damage [19-5]. In 1907, Hayden [19-6], reporting on tests with lead electrodes, showed that the corrosive effect of small ac currents was less than 0.5 percent as compared with the effects of equal dc currents.

Later work using higher densities of ac current has shown that ac corrosion can be a major factor in concentric neutral corrosion. See Section 3.2.4.

2.6 Local Cell Corrosion

Local cell corrosion, also known as differential aeration in a specific form, is caused by electrolytic cells that are created by an inhomogenous environment where the cable is installed. Examples include variations in the concentration of the electrolyte through which the cable passes, variations in the impurities of the metal, or a wide range of grain sizes in the backfill. These concentration cells corrode the metal in areas of low ion concentration.

Differential aeration is a specific form of local cell corrosion where one area of the metal has a reduced oxygen supply as compared with nearby sections that are exposed to normal quantities of oxygen. The low oxygen area is anodic to the higher oxygen area and an electron flow occurs through the covered (oxygen starved) material to the exposed area (normal oxygen level).

Differential aeration corrosion is common for underground cables, but the rate of corrosion is generally rather slow. Examples of situations that can cause this form of corrosion include a section of bare sheath or neutral wires that are laying in a wet or muddy duct or where there are low points in the duct run that can hold water for some distance. A cable that is installed in a duct and then the cable goes into a direct buried portion is another good example of a possible

differential aeration corrosion condition.

Differential aeration corrosion turns copper a bright green.

2.7 Other Forms of Corrosion

There are numerous other forms of corrosion that are possible, but the most probable causes have been presented. An example of another form of corrosion is microbiological action of anaerobic bacteria which can exist in oxygen-free environments with pH values between 5.5 and 9.0. The life cycle of anaerobic bacteria depends on the reduction of sulfate materials rather than on the consumption of free oxygen. Corrosion resulting from anaerobic bacteria produces sulfides of calcium or hydrogen and may be accompanied by a strong odor of hydrogen sulfide and a build-up of a black slime. This type of corrosion is more harmful to steel pipes and manhole hardware than to lead sheaths.

3. CONCENTRIC NEUTRAL CORROSION

This section will concentrate on the corrosion mechanisms associated with concentric neutral, medium voltage power cables. [19-10]. The most probable causes of concentric neutral corrosion include:

- Differential aeration.
- Stray dc current flow.
- DC current generated through ac rectification.
- AC current flow between neutral and earth.
- Galvanic influence with semiconducting layer (unjacketed cables).
- Galvanic influence of alloy coating and copper neutral wires and other action from dissimilar metals.
- Soil contaminants.

Electric power systems had used copper directly buried in the ground for over 60 years without problems being experienced. Most of the applications consisted of butt wraps under poles and substation ground grids. The successful operation led to a complacency when underground residential distribution cables began to be installed in vast quantities after 1965.

Although the number of cable failures caused by neutral corrosion were very small, when these cables did fail for other reasons it became clear that neutral corrosion was taking place in situations that were not anticipated.

3.1 Research Efforts

EPRI funded a series of projects to study the problem and to suggest remedies: [19-8]--[19-14]. The subjects include mechanisms of corrosion, cathodic protection methods, procedures for locating corrosion sites, and step-and-touch potential data for jacketed as well asunjacketed cable.

3.2 Mechanisms of Concentric Neutral Corrosion

Differential aeration is one specific type of local cell corrosion and is probably the most frequent cause of neutral corrosion. Fortunately, this is a relatively slow form of attack. This type of corrosion is caused when metal is exposed to soils or water having a difference in oxygen content. Examples of this are:

- Soils with different grain sizes.
- Cable going from a direct buried environment to a conduit.
- A conduit run that has a section with standing water and another section that has an unlimited supply of oxygen.
- Jacketed cable spliced to unjacketed cable.

The key concept here is the dissimilar environment and oxygen supply for a run of cable. It can occur in a small crevice made by a large grain of sand or stone in contact with the copper neutral conductor. Areas of low aeration change to an area that is well aerated. This form of corrosion is frequently caused when special backfills are brought in to replace the native soil. The native soil usually has a consistent grain size while the imported material may have quite a different grain size. Pockets are thereby formed.

Another very frequent cause of this form of corrosion is where an unjacketed cable leaves a conduit (such as under a street) and enters the earth. The same sort of cell is created by having a low section of conduit that is filled with water while the adjacent section is in a dry conduit. The use of an overall jacket (either insulating or semiconducting) eliminates this condition.

Stray dc current flow problems are very similar to the lead sheath condition previously described. This situation is frequently encountered when an anode

that is used to protect a gas pipeline that is installed in close proximity to an unjacketed cable. This damage occurs very rapidly.

Stray dc current causes dissolution of the copper where anions are present that contribute to the reaction. The rate of dissolution may not follow Faraday's law precisely because of other electrochemical oxidation reactions that occur in parallel.

DC current flow can be generated through ac rectification across a film of copper oxide. Copper neutral wires quickly develop an oxide coating. This coating provides a rectification boundary so that ac current is restricted from flowing back to the neutral wires. This is similar to the situation in 3.2.4.

AC corrosion was not recognized as a serious problem in the initial URD systems. The opinion was that while ac current flow might take off metal during one half cycle, the other half cycle would bring it back. The concept of rectification was commonly discussed as a possible explanation for ac corrosion in the 1960s. It was not until the 1970s that ac corrosion was recognized as a major concern for copper neutrals. The Final Report of EPRI EL-4042 [19-12] published in 1985 stated that the effect of high ac current density was creating this rapid corrosion mechanism on bare URD and UD cables.

Above some threshold of ac current density, the positive cycle tends to dissolve more metal than the negative cycle can plate back. Especially in cables with large conductors that are heavily loaded (such as feeder cables), the amount of current that can flow off the neutral wires at one point and then back on at another is quite large. Another explanation of this flow of current off and then back on the neutral wires is that shifts in potential exist along the cable length due to the differences in the current densities.

Galvanic influence with the semiconducting insulation shield material and bare or tinned copper is another form of concentric neutral corrosion. A voltage differential exists between the carbon in the semiconducting layer and the neutral wires. Corrosion, although not a widespread cause of failure, must be considered.

Dissimilar metal corrosion is probable if plating is used on the neutral wires and no jacket is applied over these wires. Areas of bare copper may exist during the factory plating process or are created by mechanical scraping during handling and field installation efforts. The result is a local cell corrosion due to the two different metals.

Research has shown that bare wires out perform plated wires in the field. When jackets are used, bare copper wires are recommended and are almost always

specified.

Soil contaminants and other direct chemical action is another source of problems for URD cables. Examples of this are high quantities of chemicals in the soil such as from fertilizers, peat, cinders and decaying vegetation. Decaying vegetation produces hydrogen sulfide that reacts rapidly to deteriorate copper.

Combinations of the previously discussed corrosion mechanisms do occur in the real world. Multiple sources of corrosion accelerate the problem.

4. JACKETS

An overall jacket is the preferred construction for new cable. Both insulating and semiconducting jackets have demonstrated their ability to virtually eliminate corrosion of the neutral wires. An encapsulated jacket made with linear low density polyethylene is the type most frequently specified. See Chapter 8 for a complete discussion of jackets.

5. CATHODIC PROTECTION

Cathodic protection [19-7] can be applied to the copper neutral wires of existing cable that did not have a jacket or where the jacket may be damaged. An obvious place where cathodic protection should be considered is where a bare neutral cable goes from a direct buried environment to a conduit as under a road. Another is where a long section of jacketed cable is spliced onto a short section of existing bare neutral cable. Here the short section will be even more vulnerable to corrosion.

Noteworthy efforts have been expended towards solving this concern and the reference section contains excellent sources of advice regarding design and installation recommendations.

6. LOCATION OF CORROSION SITES

The existence of deteriorated copper neutral wires is an unwelcomed fact. How to identify their existence and then locate the precise site of the corrosion has shown great advancement in recent years. Several technologies are presently available.

6.1 Resistivity Measurements of Neutral Wires

Resistive techniques are used to measure the resistance of neutral wires of installed cables. Instruments are available for testing the resistance of the neutral wires while the cable is energized. This value is compared with the original

resistance for that length of cable and the size and number of original wires. A new or undamaged cable would show a resistance ratio of 1 while a cable that has half of the wires remaining would have a ratio of 2.

6.2 Location of Deteriorated Sites

If the reading of the resistance ratio warrants, the precise location of the corroded area can be obtained by using a form of time domain reflectometry (TDR). This equipment is similar to that used for locating cable faults. [19-15].

Damage to the a neutral wire must be great enough so that a reflection can be seen on the screen of the TDR. This may mean that a wire with only pitting may not be identifiable, and the cable would appear to be sound. The reflection of that wave from the end of the cable has a lower amplitude than intact wires. A cable with uniform corrosion may not be seen, but discreet sites cause reflections and are readily detected.

7. REFERENCES

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